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NOVEMBER, 1944
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With which is incorporated The Institution of Aeronautical Engineers

Edited for the Council by Capt. J. LAURENCE PRITCHARD, Hon. Fellow

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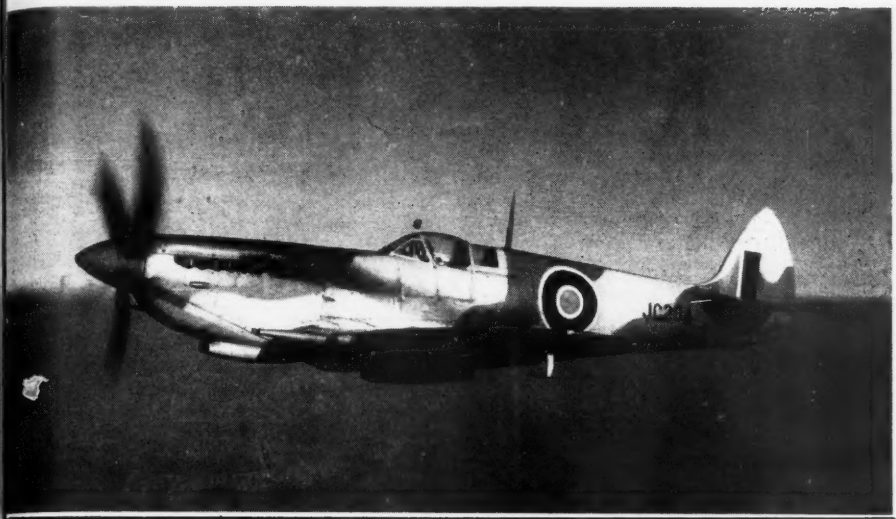

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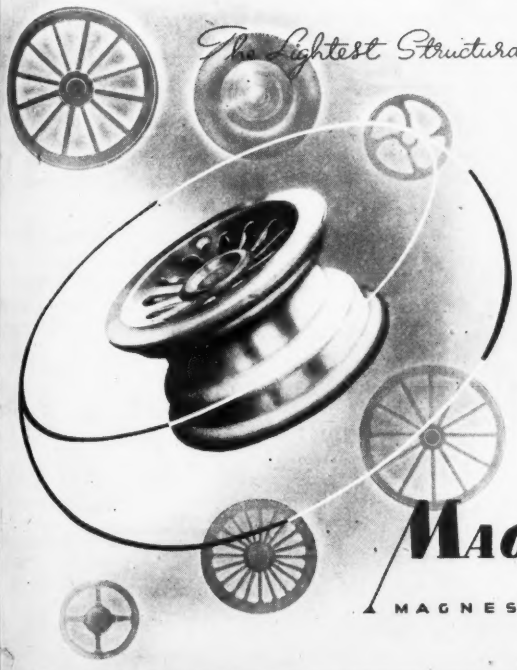

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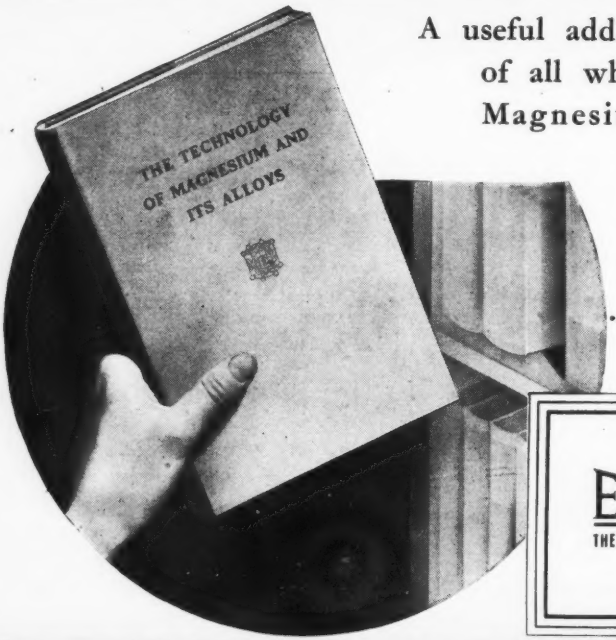

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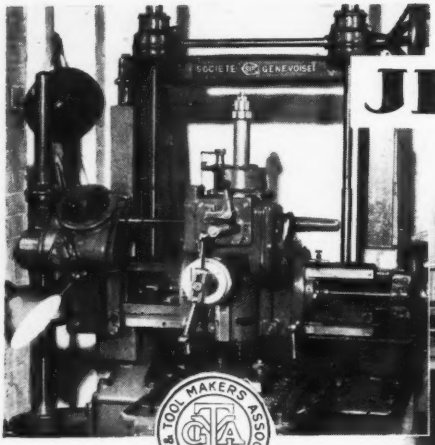

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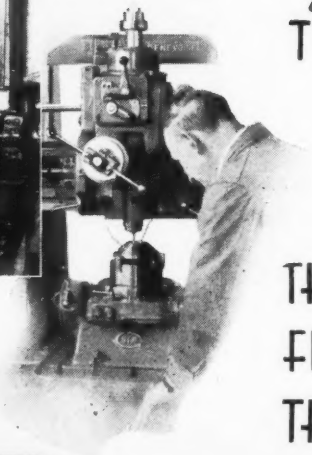

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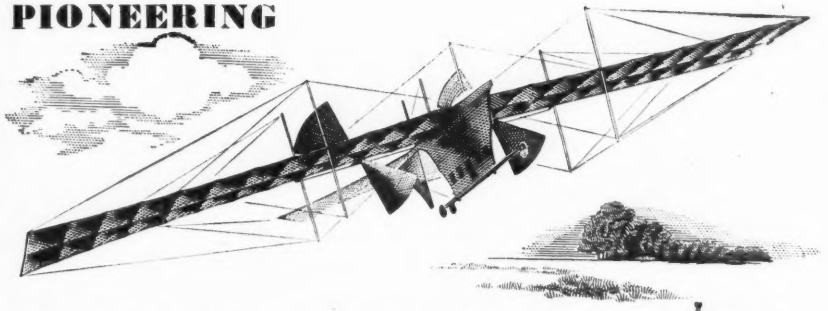

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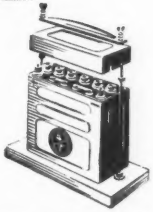

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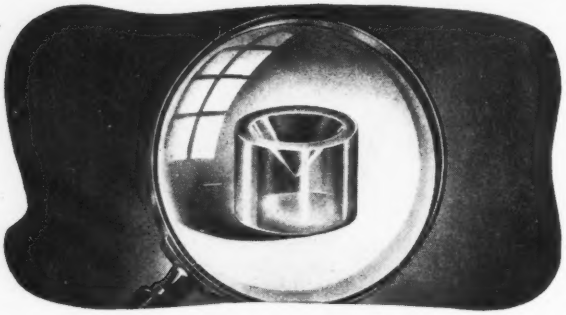

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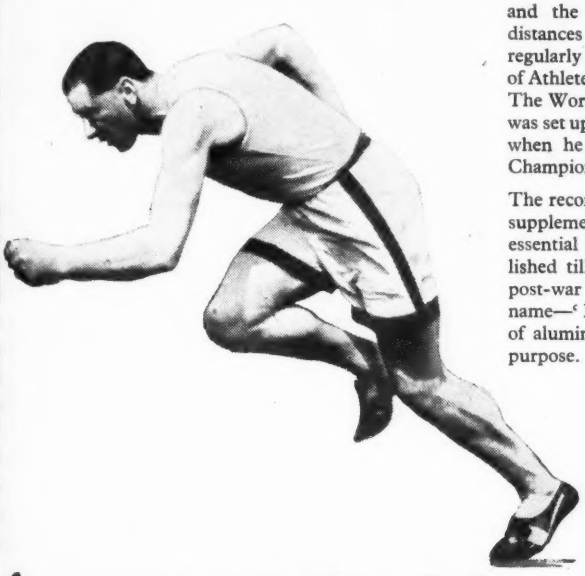

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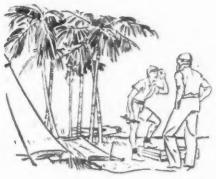

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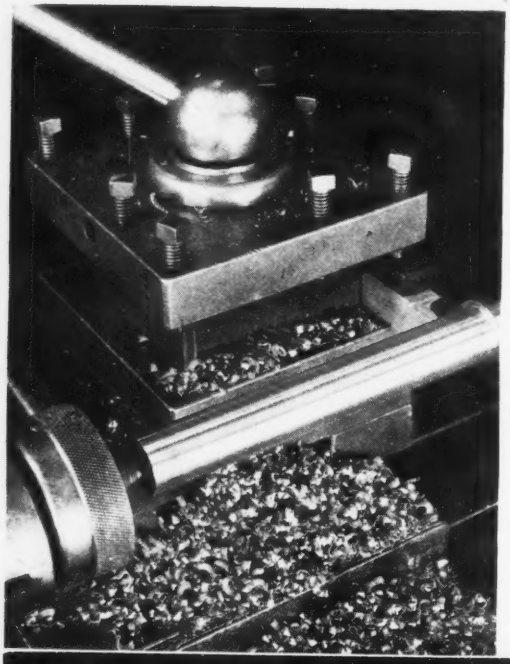

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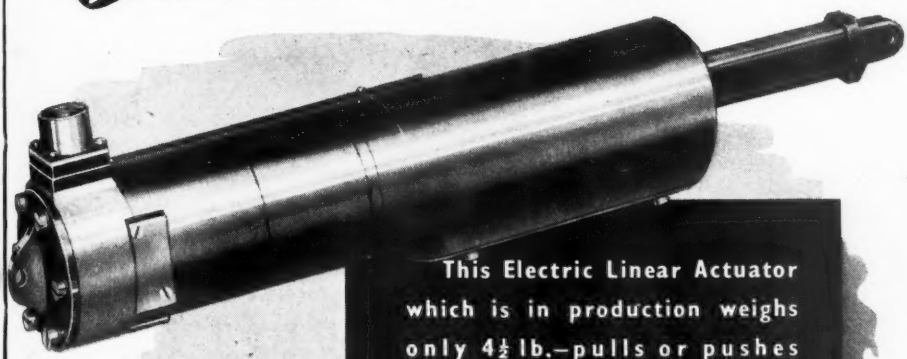

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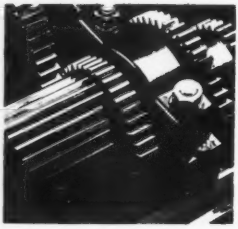

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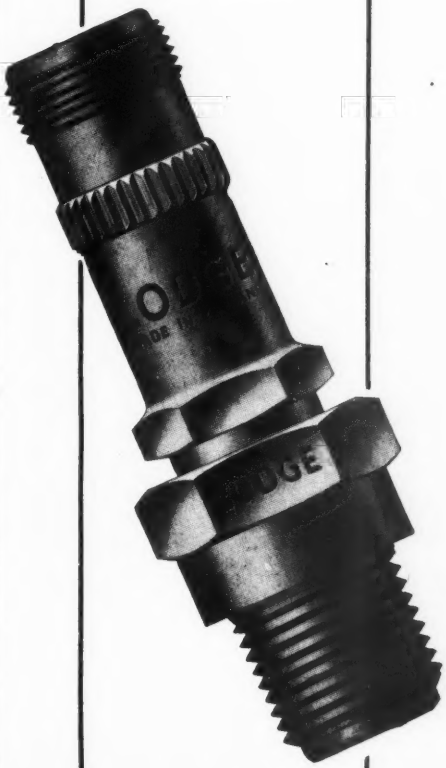

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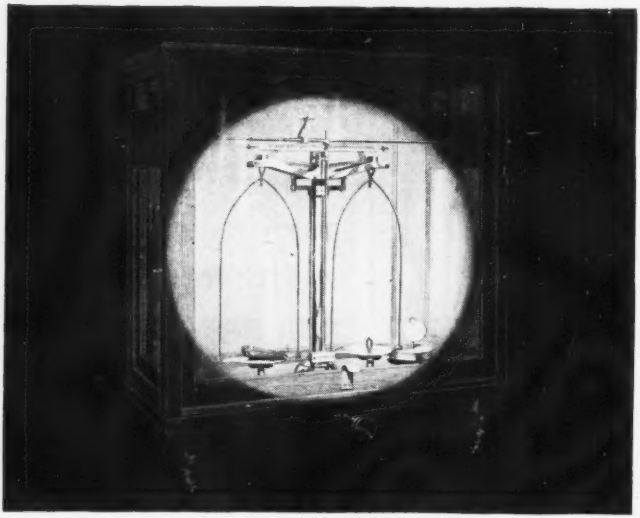

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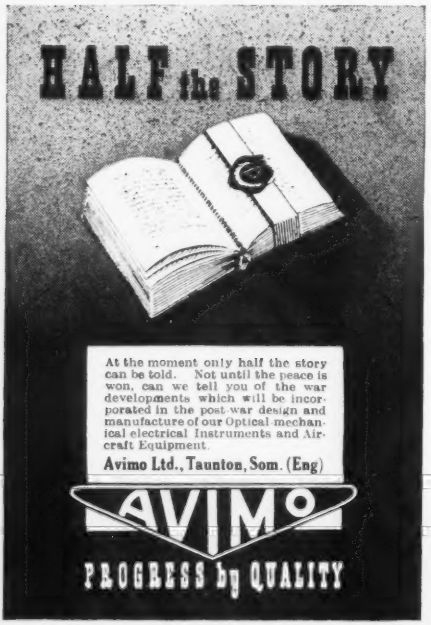
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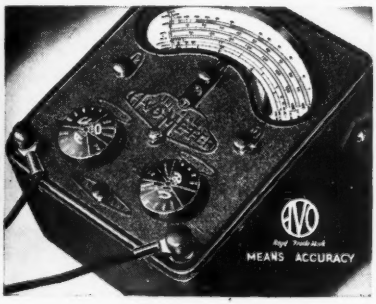

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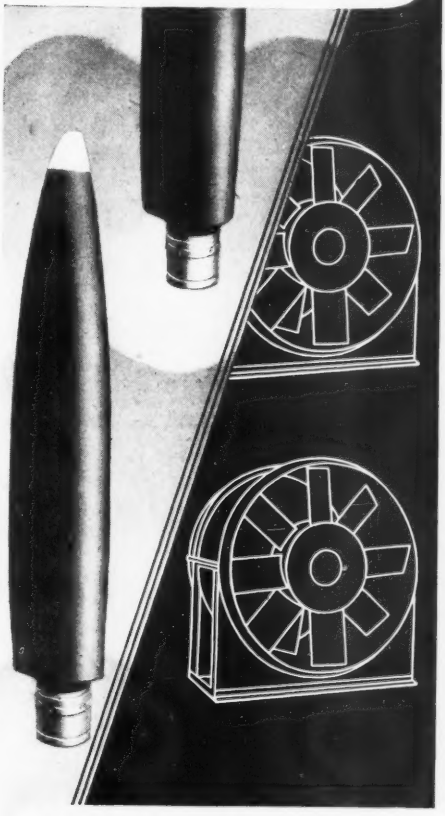

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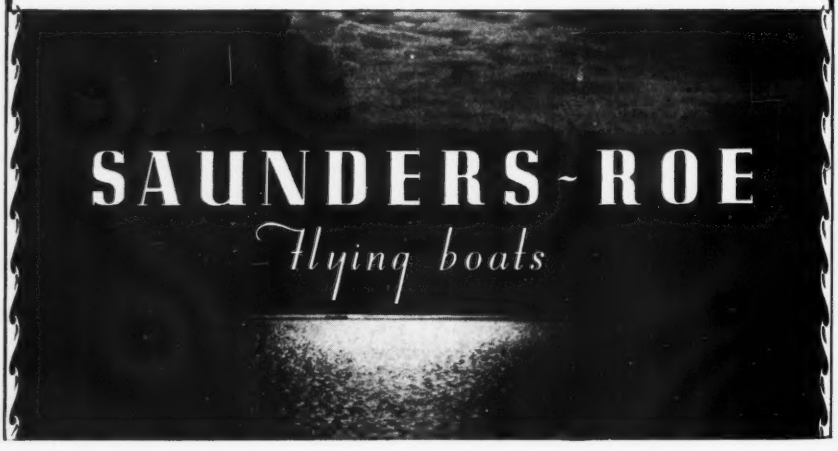

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OF
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With which is Incorporated The Institution of Aeronautical Engineers.

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THE JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY *was founded in 1897 in succession to the* ANNUAL REPORTS.

For the opinions expressed in Papers that are signed or initialled the authors alone are responsible. None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless such is definitely stated to be the case.

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PRINCIPAL NOVEMBER CONTENTS.

Two-Spar Wing Stress Analysis. W. J. Goodey.
Research in Australia.
The Strength of Valves at Closing. W. Zalewski.
Designing for the Customer. J. G. Wills.
Indium in Aviation. W. S. Murray.
Administrative Engineering in the U.S.A. D Tiranti and C. A. Whipple.

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MONTHLY NOTICES

NOVEMBER, 1944.

Increase in Price of the Journal.

The Council have decided that on and from January 1st, 1945, the price of the Journal should be increased to 7s. 6d. per issue to non-members (£4 10s. per annum).

Lectures, 1945.

The following programme of lectures has been arranged to be held at 6.30 p.m. in the Lecture Hall of the Institution of Mechanical Engineers, Storey's Gate, St. James', S.W.1 (by permission of the Council of the Institution). Members do not need admission tickets, but visitors must obtain a ticket through a member :—

1945.

Thursday, 15th February.—Aircraft Wheels and Brakes, by Mr. J. Wright.

,, 1st March.—Control Surface Design, Joint Lecture by Mr. M. B. Morgan and Mr. Thomas.

,, 8th March.—Electrics for Aircraft, by Mr. C. G. A. Woodford, A.F.R.Ae.S.

,, 22nd March.—Hydraulics for Aircraft, by Mr. R. H. Bound, F.R.Ae.S.

,, 5th April.—Modern Experimental Work on Aeroplane Structures, by Dr. A. G. Pugsley, F.R.Ae.S.

,, 31st May.—33rd Wilbur Wright Memorial Lecture, by Mr. T. P. Wright, Hon.F.R.Ae.S.

Branch Lectures.

Derby Branch.

Lectures are held in the Rolls-Royce Welfare Hall, Nightingale Road, Derby, at 6.30 p.m.

Monday, 6th November.—Sir Frederick Handley Page, C.B.E., F.R.Ae.S. (subject to be announced later).

,, 4th December.—Annual General Meeting. Lecture and film, "The Ace of Blades."

Luton Branch.

Lectures are held at the Technical College, Luton, at 7.15 p.m.

Wednesday, 6th December.—Design and Operation of Deck Landing Aircraft, by Mr. G. E. Petty, F.R.Ae.S.

,, 10th January, 1945.—Flight Testing of Aircraft Control and Stability, by Dr. D. Cameron.

Medway Branch.

Lectures are held at 7.15 p.m.

Monday, 13th November.—Some Aspects of the American Aircraft Industry, by Dr. D. M. A. Leggett, A.F.R.Ae.S.

,, 11th December.—An evening of films.

,, 8th January, 1945.—Light Alloy Castings, by Mr. F. Hoult.

,, 12th February.—Compressibility, by Dr. W. F. Hilton.

,, 12th March.—Engine Installations, by Mr. F. Mayer.

,, 9th April.—Work in an Experimental Seaplane Tank, by Mr. L. Smith.

BELFAST BRANCH.

Lectures are held in the Central Hall, College of Technology, at 6.30 p.m.

Monday, 20th November.—Aerodynamics and Strength, by Mr. G. I. Robinson.

,, 11th December.—Drawings and Lofting, by Mr. H. G. Parker, A.F.R.Ae.S., and Mr. Patrick.

,, 29th January, 1945.—Production and Works Organisation, by Mr. W. Browning, A.F.R.Ae.S., A.M.I.Mech.E., M.I.P.E.

,, 26th February.—Production Control, by Mr. M. R. Beaney, A.F.R.Ae.S., A.M.P.E.

,, 26th March.—Inspection, by Mr. H. H. Hall, A.F.R.Ae.S.

,, 16th April.—Test Flying, by Mr. J. Lankester Parker, F.R.Ae.S.

BRISTOL BRANCH.

Lectures are held in the Conference Room, Bristol Aeroplane Company, Filton House, Bristol, at 6.30 p.m., by kind permission of the Directors.

Tuesday, 14th November.—Possible Developments in the Design of Air-Cooled Engines, by Mr. B. G. Markham, M.A., A.F.R.Ae.S.

Thursday, 23rd November.—The Bird and the Aeroplane, by Captain J. Laurence Pritchard, Hon. F.R.Ae.S.

Thursday, 14th December.—Pressurising and Air Conditioning at High Altitudes, by D. R. Pobjoy.

Tuesday, 16th January, 1945.—Flight Testing, by Mr. E. T. Jones, A.F.R.Ae.S.

Tuesday, 6th February.—Plastics—Their Industrial Application, by Mr. H. Carl Martin.

Tuesday, 20th February.—Flying Boats, by Mr. A. Gouge, F.R.Ae.S.

Tuesday, 6th March.—Development in Rotating Wing Aircraft, by Mr. R. Hafner.

Tuesday, 20th March.—Film Night and Annual General Meeting.

Zaharoff Chair of Aviation.

It should be noted that Professor Bairstow's successor in this office is Mr. A. A. Hall, and not Mr. A. H. Hall as stated in last month's Notices.

Royal Air Forces Association.

The Royal Air Forces Association is appealing for funds to help all ex-R.A.F. and W.A.A.F. personnel of all ranks. The President is Lord Trenchard and the Chairman of Council Air Chief Marshal Sir John M. Steel.

The Association is actively concerned in promoting the welfare of R.A.F. and W.A.A.F. personnel, not only by providing places where they can meet, but by help and advice on employment, legal questions, pensions, etc., and they work in close co-operation with other bodies, as the R.A.F. Benevolent Fund.

It is hoped that their appeal for funds will be generously answered. All contributions should be sent to Air Commodore E. L. Howard-Williams, Chairman of the Executive Committee, 105a, Gloucester Road, S.W.7.

Election of Members.

The following members have recently been elected:—

Associate Fellows.—Leslie Aitchison, Leslie Frederick Atkinson (from Graduate), Peter Eugene Bish (from Graduate), Geoffrey William Bone, Jerzy Michat Brzustowski, William Close, Frank Grinsted (from Graduate), Christopher Webster Jones, Tom Joseph Percival Joy (from Graduate), Arthur Jacob Mautner, Frank Henry Ordidge, Matthew Sausse Slattery, Joseph Robert Standring, Jacob Samuel Shapiro, Joseph Donald Stranks, Charles Frank Stubbs, Ivor Lewis Thomas.

Associates.—Frank Miles Clark, Robert John Payne Crawfurd, Jeremiah Joseph Crowley, William John Leslie Davies (from Graduate), Wilfred Dowdall, Samuel Green Fenwick, George Edward Finch, Douglas Gerald Seafield Grant, Gordon William Thomas Gray, John Bryant Hawton, William Charles Hill, Herbert Hickson, Richard Henley Howard, William Redvers Kilminster, Leonard Sidney Marrington, Charles Merryfull, William Davies Morris, Esmond John Hugh Fulford Moreton, William David Morgan, William Turnbull Neill, Frederick James O'Connell, Horace Sidney Patrick, Eric Royce Platford, Reginald Nunley Playford, Kenneth Henry Porter, Norman Llewellyn Prewett, Frank Henry Robertson, Charles Harvey Robinson, William Bruce Smith, Harold Victor Stagg, Thomas Briggs Stelling, Clifford Harvey Tibbles, Christopher Tom Walkington, John Wells, Alexander Zielony (from Graduate).

Graduates.—Gordon Desmond Bateman, Douglas Thornton Brown (from Student), Arthur Charles Caporn, John Alexander Jefferson-Loveday, Norman Hugh Le Gallais, Thomas Harry Merchant, Peter George Mobsby (from Student), Woolf Petrook, Nathan Owen Rawlinson, James William Ritchie, Charles George Woolven.

Students.—John Cecil Bailey, Arthur Baker, Ronald Vincent Belvoir, John Reginald de Boer, Geoffrey Frank Briginshaw, Maurice C. Curties, John Lewis Cutler, John Lewis Dickson, Anthony Edward Francis Donovan, Owen Desmond Arthur Charles Furlong, John Anthony Hay, Ivan Bernard Henshaw, Ralph Spenser Hooper, Douglas Norcliffe Hubbard, Edward Claude Hubert, Thomas George Kent, Hugh John Julian King, Gilbert Frederick Lloyd, Desmond Walter Mitchell, Ralph William Mullins, Peter Edward Thomas Oakley, Frederick Arthur Quinton, Hugh Everard Scrope, Michael Charles George Smith, Morris Ira Speigel, Robert Douglas Tyler, Stanley Ralph Tyler, Derrick William Moore West.

Companions.—William Henry Brown, George Herbert Ivan Cornwell, Austin Eastwood, Richard William Edwards, Carl Griffith.

Acknowledgments.

The Council acknowledge with grateful thanks the gift of a wooden model used for the wind tunnel tests for the 1927 Schneider Trophy aircraft, presented by Mr. J. S. Irving, Associate Fellow.

The Council also wish to acknowledge the gift of Journals from Squadron Leader A. E. Harrop, A.F.R.Ae.S., and Mr. A. C. Barlow, F.R.Ae.S.

Additions to the Library.

Pamphlets in italics with location reference following in brackets.
Books marked * or ** may not be taken out on loan.

B.a.327.—*Hawker "Tempest" in Action. Ministry of Aircraft Production.* (*Press release*, 18/10/44.) (Y.3.iii.31.)

*B.g.140.—Jane's All the World's Aircraft, 1943. Ed. by Leonard Bridgman. Sampson, Low and Marston. 1944. £3 3s. od.

*B.g.141.—Aircraft Recognition. (Vol. 1, revised.) R. A. Saville-Sneath. Penguin Books, Ltd. 1943. 9d.

BB.c.90.—*Air Braking by Reverse-Thrust Propellers. Curtiss-Wright Corp.* (*Press release*, 2/10/44.) (Y.7.a.17.)

**D.a.A.25.—Aeronautical Statutes and Related Material. Civil Aeronautics Authority, Washington. 1940.

*D.a.B.83.—*Air Registration Board: Chairman's Report*, 1943-44. (Y.6.2.b.31.)

*D.a.B.84 and 85.—*International Air Transport* (*Cmd.* 6,561). *H.M.S.O.*, 1944. 1*d.* (PD.2.a.14 and 15.) Two copies.

*D.a.H.7.—Poland's Share in Pre-War Air Transport. Polish Ministry of Industry, Commerce and Shipping. 1944.

D.b.222.—*Post-War Air Transportation Rates. Curtiss-Wright Corp.* (*Press release*, 29/8/44.) (Y.6.i.40.)

D.b.223.—*Expansion of Eastern Air Lines "Great Silver Fleet." Curtiss-Wright Corp.* (*Press release*, 4/10/44.) (Y.6.i.41.)

*D.b.224.—*Parliamentary Debates: House of Lords. Vol.* 133, *No.* 89. 12/10/44. *Post-War Civil Aviation.* (Y.20.ii.)

*E.f.106.—*Notices to Licensed Aircraft Engineers, Nos. 1 and 2. Air Registration Board*, 1944. (File Case.)

*E.e.13.—Handbook for M.A.P. and M.O.S. Contractors. S. J. Noel-Brown. Engineering Industries Association. 1944.

G.c.28.—*Further Experiments on the Damping Capacity of Metals. W. H. Hatfield and Others. N.E. Coast Inst. of Engineers and Shipbuilders.* (*E. and F. Spon.*) 1944.

G.d.18.—*Chromate Passivation of Zinc and Cadmium.* (*Metal Processing Bulletin No. P.5.*) *Rushton Organisation*, 1944. (PG.1/25.)

G.e.J.26.—Metallography of Magnesium and its Alloys. W. Bulian and E. Fahrenhorst. F. A. Hughes and Co. 1944. 15/-.

L.f.12.—The Chichester Sun Compass. Francis Chichester. Allen and Unwin. 1944. 5/-.

L.k.44.—*Air Crew in Their Element. Major V. E. Henderson. University of Toronto Press.* 1942. 2/6. (PL.3/10.)

*Q.a.25/37.—Subject Headings for the Aeronautical Index. N. H. Randers-Pehrson. Federal Works Agency, New York. 1940.

S.d.91.—Night Bombing. Hector Hawton. Thos. Nelson and Sons. 1944. 5/-.

UC.8.—*Australian Council for Aeronautics: Reports* (1944):—

A.C.A.-3.—Izod, Tensile and Hardenability Tests on X.4130 Chrome-Molybdenum Steel. A. R. Edwards.

A.C.A.-4.—A Consideration of the Design of Wind Tunnel Constructions. G. K. Batchelor and F. S. Shaw.

A.C.A.-5.—Interference on Wings, Bodies and Airscrews in a Closed Tunnel of Octagonal Section. G. K. Batchelor.

*UU.c.—*National Advisory Committee for Aeronautics* (*U.S.A.*): *Technical Memoranda*:—

No. 1064. Methods of Stress Calculation in Rotating Disks. S. Tumarkin. (C.A.H.I., No. 262, 1936.)

No. 1065. D.V.L. Angular Velocity Recorder. W. Liebe. (Luftwissen. Aug., 1938.)

No. 1071. Determination of the Actual Contact Surface of a Brush Contact. R. Holm. (Siemens-Werken, Vol. 17. No. 4, 1938.)

No. 1072. Surface Structure of Ground Metal Crystals. (Naturwissenschaften, Vol. 20, Nos. 22-24, 27/5/32.) W. Boas and E. Schmid.

No. 1073. Axial Superchargers. A. Betz. (Jahrbuch der D.L.F.F. 1938.)

No. 1074. The Frictional Force with Respect to the Actual Contact Surface. R. Holm. (Siemens-Werken, Vol. 17, No. 4, 1938.)

*X.a.54.—S.A.E. Handbook, 1943. Society of Automotive Engineers, U.S.A.

J. LAURENCE PRITCHARD, *Secretary and Editor.*

FACTORS OF SAFETY—OR OF HABIT?

By W. Tye, B.Sc., A.F.R.Ae.S.

Introduction.

1. Our engineering habits form slowly, and once formed are slow to change. This is perhaps less true in aeronautics than in other branches of engineering. Nevertheless some aeronautical customs are deeply rooted, so much so that it is easy to confuse the superstructure of habit with the basic foundations. In this article I have reviewed some of the customary methods of specifying strength conditions and have tried to disentangle the underlying principles. Current changes in these methods emphasise the need of a proper appreciation of the principles, and a study of these principles suggests even more radical changes of methods in future.

2. In a brief article it is impossible to cover the whole field of strength requirements. To give a focus to the argument, I have confined this article to discussion of the main "symmetrical flight manœuvres," but the general theme is equally applicable to any kind of loading condition. The symmetrical flight manœuvres are those flight manœuvres which result from an action on the part of the pilot (thus excluding loading due to atmospheric gusts) and which involve motion in the pitching plane only (thus excluding rolling, spinning, yawing, etc.). In such a manœuvre the loads sustained by the aeroplane are primarily dependent on the speed of flight and the acceleration of the aeroplane normal to its flight path.

Previous Practice—Selected Stressing Cases.

3. During a single flight the aeroplane is subjected to a variety of speeds and accelerations, and hence the structure sustains loads which vary widely in magnitude and direction. When the time period considered is the life of the aeroplane, the possible loading conditions become even more numerous. Nevertheless, the designer has to provide strength to meet such numerous conditions if the aeroplane is to remain airworthy, and the question at once arises as to how he can do this without an intolerable amount of calculation.

4. For many years the problem was solved by the responsible authority (then the Air Ministry) selecting a limited number of stressing cases with the intention that if the aeroplane were designed to meet these cases it would be capable of withstanding the infinite number of other possible conditions. In terms of symmetrical manœuvring flight these selected cases were:—

"Centre of Pressure Forward"	—giving high normal acceleration at low speed,
"Centre of Pressure Back"	—giving high normal acceleration at high speed,
"Fast Glide"	—giving small acceleration at high speed.

In addition acrobatic aeroplanes were stressed for:—

"Terminal Velocity"	—giving zero normal acceleration at very high speed,
"Inverted Flight"	—giving negative normal acceleration at low speed.

5. This system of selected cases was on the whole successful but was open to objections. One objection was that there was an almost unavoidable tendency to make each case a little more severe than was strictly necessary in order to ensure that other conditions were covered. There was also a tendency to simplify each case at the expense of retaining an accurate conception of its physical significance. This system may be satisfactory for a particular class of aeroplane within a given generation of aeroplanes, but as design practice changes the over-simplified stressing case may depart widely from the truth, and this may well be a hindrance to development in design. For these, and for other reasons, the tendency in the last few years has been to replace the system of selected stressing cases of a semi-arbitrary kind by a system in which the conditions are specified in a more general manner.

Present Practice—"Envelope" Cases.

6. The best known of the envelope cases is the "flight envelope," which is in general use in this country and in the United States. It is fitting to pay tribute to Dr. P. B. Walker, (then of the Royal Aircraft Establishment), who was responsible for much of the pioneering work associated with the introduction of this scheme in this country.

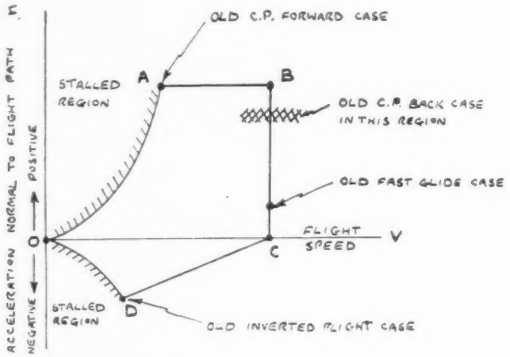


FIGURE 1

FLIGHT ENVELOPE OR n-V DIAGRAM

7. The "flight envelope" covers all probable conditions of symmetrical manœuvring flight instead of the few isolated points specified in the previous system. It is based on the previously mentioned fact that the loads sustained in symmetrical manœuvring flight are mainly functions of the normal acceleration n and the flight speed V. Other variables, such as pitching acceleration, have only a secondary importance. We can therefore specify the whole range of symmetric manœuvres by drawing a diagram which defines the range of n and the range of V. Such a diagram, which is called an n-V diagram, is illustrated in Fig. 1. The line AB represents the highest expected normal acceleration: BC represents the highest expected speed, and point D the highest normal negative acceleration at low speeds. The curved lines OA and OD represent the stall—it would be impossible to achieve a value of n above the line OA or below the line OB, because the wing would be beyond its stalling incidence. The link between the previous and the present system is also illustrated in Fig. 1, on which are plotted some of the old selected cases.

V-G Records.

8. I must now digress for a moment to discuss a valuable source of information on which the *n-V* diagram may be based. The *V-G* recorder is simply an instrument which when suitably installed in an aeroplane keeps a continuous record of the speed of flight and the associated normal accelerations. The *V-G* record is in fact the experimental counterpart of the design *n-V* diagram. A typical *V-G* record is sketched in Fig. 2. It is clear that during a flight a particular combination of *n* and *V* may occur several times and the recording needle then crosses the same point several times over. The central part of the record thus becomes a maze of lines which get progressively denser the longer the recording slide is left in the instrument. Sometimes there are isolated lines outside the central blur (as in the record sketched) and these lines result from particularly high accelerations and speeds. Whether such lines are present or not it is reasonable to assume that the extreme boundary of the record represents manœuvres which occur once in so many hours—the number of hours being the time (in flying hours) during which the *V-G* recorder has been accumulating data in the aeroplane. In practice, the recording slide in the *V-G* recorder is changed fairly frequently, thus providing statistical evidence of the boundary shape. Approximate methods exist whereby the recorded data can then be expressed in terms of *n-V* boundaries corresponding to any desired number of hours flying. Fig. 3 illustrates such boundaries.

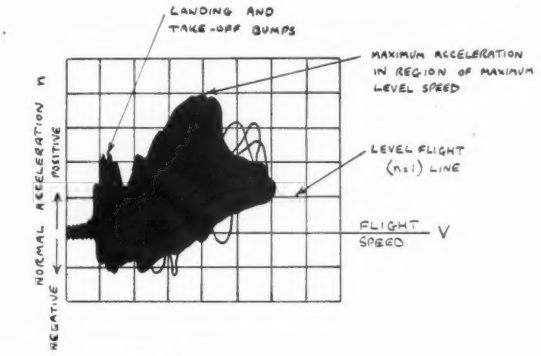


FIGURE 2.

TYPICAL V-G RECORD.

9. Before discussing how these experimentally obtained *n-V* boundaries can be used for design purposes, it is of interest to note the general shape of the boundaries sketched in Fig. 3 (which though not relevant to any particular aeroplane are fairly typical). Not unnaturally the sharp corners of the simple *n-V* diagram of Fig. 1 are not apparent in the boundaries obtained experimentally. The sharp corner at *B* is most noticeably severe, and it is to be expected that, as *V-G* evidence accumulates, it will become possible to specify *n-V* diagrams for design purposes, which adhere more closely to the true *V-G* boundary shapes.

Frequency of Occurrence of External Loads.

10. It has been pointed out that from the *V-G* records it is possible to obtain *n-V* boundaries corresponding to any given frequency of occurrence. The choice of a particular boundary depends mainly on how safe it is intended the resulting aeroplane should be, and in turn the desired degree of safety depends on the use to which the aeroplane will be put. It is impracticable to build aeroplanes so strong that they cannot be broken—such aeroplanes would have such heavy

structures that they would be useless—and the need thus arises to decide just how safe each class of aeroplane should be.

11. The frequency of structural failure which is acceptable is to some extent influenced by the frequency of other kinds of accident. For example, in the military aeroplane the losses due to enemy attack are largely unavoidable and an occasional structural accident would not materially increase the total accident plus loss rate. It may in fact be preferable to economise in structure weight at the cost of a small number of structural accidents if by so doing it becomes possible to carry heavier armament and armour, thus reducing the relatively more serious rate of loss arising from enemy attack. A limit to this process of balancing one kind of accident against another is of course set by the fact that in no circumstances must the pilot lose confidence in the structural qualities of his aeroplane. In general, however, it seems that, in the military aeroplane, the *total* losses should be reduced to a minimum and the design should be adjusted so that this is achieved.

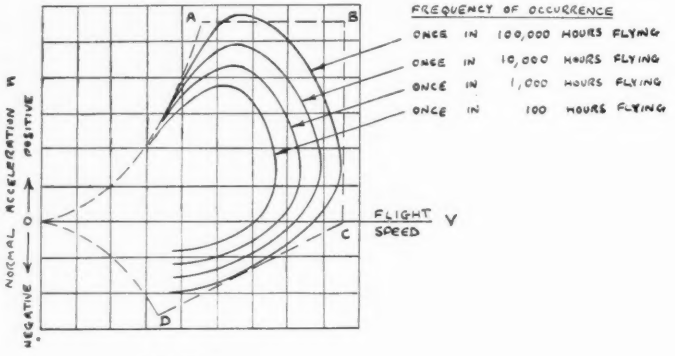


FIGURE 3

INTERPRETATION OF V-G DATA

12. In the civil aeroplane the structural accident is of more significance and the associated accident rate must be reduced below a correspondingly lower level. It is in fact sometimes argued that the structural accident rate for civil aeroplanes should be zero, but I am doubtful whether this is true. Provision of safety is costly—fortunately the cost diminishes as we learn more about design—and the question reduces to how much the passenger is willing to pay for safety. We hope the day will come when air transport is as safe as travel by railway or steamship. When this stage is reached it is doubtful whether the average passenger would consider it worth while paying a higher fare, if by so doing the already high standard of safety could be raised still further. It is beyond the scope of this article to suggest acceptable accident rates, but sufficient has been said to show that there are reasonable arguments on which to base the choice.

Proof and Ultimate Failure.

13. So far " structural failure " and " accident due to structural failure " have been treated as synonymous, but this requires qualification. The effort to keep the rate of structural failure within reasonable limits arises from the need—

to avoid accidents which result in fatalities or injuries, and
to avoid accidents which result in the need for repairs to the aeroplane.

Failures which involve complete fracture of the primary structure (ultimate failures) almost certainly result in the former kind of accident. Failures in which the

structure is distorted slightly probably result in repair work, but may not cause a serious accident. Between these two extremes are the cases where the structure is fairly seriously distorted, and the more serious this distortion, the greater the probability of a major accident developing from the reduced control and stability. Serious distortion may also cause a redistribution of the internal stresses and of the external loads. Whereas such redistribution of the stresses usually postpones ultimate failure, redistribution of the external loads may have adverse effects and may hasten ultimate collapse. Therefore to meet the two aims stated above we must maintain appropriate standards of both ultimate and proof strength.

14. It is not immediately obvious how a reasonable ratio of proof to ultimate strength may be established. However, it so happens that most materials used in aircraft construction have proof strengths between 60 per cent. and 80 per cent. of their ultimate strengths. Confining our attention to the main flight structure, the use of such materials has led to satisfactory results in the sense that the proportion of minor accidents to major accidents is not unreasonable. Had available materials been very different from what they are—for example, had proof strengths been very much lower as a proportion to ultimate strengths than they are—it is possible that the accident state of affairs would have been less reasonable. In other parts of the structure, such as the undercarriage, failure rarely causes fatal accidents, but severe distortion may result in a disproportionate amount of repair work. In such parts of the structure more emphasis on proof strength would perhaps be beneficial.

15. There are several incidental disabilities in our present system of specifying proof and ultimate strengths. In the first instance it is difficult to decide on the degree of distortion which will render the aeroplane dangerous, and proof failure is necessarily arbitrarily defined. Using some arbitrary definition of proof strength, it is then not easy to check that the structure complies with the defined proof strength, either by calculation or by test. On the other hand ultimate failure is a clear cut condition which is readily defined, and is easily observable on test; it is however difficult to calculate ultimate strength owing to the non-elastic behaviour of the structure at high loads. Bearing the above difficulties in mind, the best we can do at present is to ensure that neither the arbitrary proof strength, nor the ultimate strength fall below their appropriate acceptable limits. The acceptable level of proof strength of the structure as a proportion of ultimate strength is rather a matter of custom and the custom differs in the standards set up by different authorities. Typical values are:

British military	0.75
German	0.75
Pre-war International	0.625
American civil	0.667

It is impossible to say that any of these is "right," but the very considerable R.A.F. experience suggests that a ratio of 0.75 is a satisfactory one. We must, however, not lose sight of the fact that our real aim is to prevent accidents of the two kinds previously mentioned, and as soon as the consequences of structural distortion in relation to accidents are more clearly understood, a more basic definition of the desired conditions should become possible.

Factors of Safety.

16. We can now link the notion of n-V boundaries of chosen frequency of occurrence with those of proof and ultimate strengths. Suppose, for example, we have selected an n-V boundary corresponding to the maximum rate at which we can accept proof failure, we must then ensure that the weakest aeroplane which may be produced has a proof strength not less than that corresponding to the n-V diagram. The ultimate strength follows at once, since past R.A.F. experience suggests that

the ultimate strength should be 1.33 times the proof strength. On this argument it seems that there is no justification for specifying ulimate factors in excess of 1.33. The habit for many years, however, has been to specify ultimate factors of 2.0 and proof factors of 1.5 or 1.25. At the time when this habit grew there was little or no data on the frequency of occurrence of loads, but the basic unfactored loads chosen were evidently ones which would occur fairly frequently. The larger factor thus offered some margin of safety over the higher, but less frequent loads. Reference to Fig. 4, however, shows that the boundaries of constant frequency are not geometrically similar. Thus in the particular case illustrated, if we specify a proof factor of 1.5 on a loading occurring once in 100 hours, with the intention of providing a small margin over the loads occurring once in 100,000 hours, we shall achieve this aim in certain regions of the n-V diagram, but will fail in other regions. The conclusion is that it is structurally safer and at the same time more economical to choose an n-V boundary of rare occurrence and to use the minimum possible factor of safety.

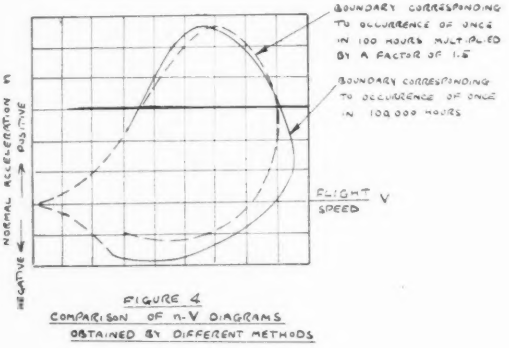

BOUNDARY CORRESPONDING TO OCCURRENCE OF ONCE IN 100 HOURS MULTIPLIED BY A FACTOR OF 1.5
BOUNDARY CORRESPONDING TO OCCURRENCE OF ONCE IN 100,000 HOURS
NORMAL ACCELERATION n
POSITIVE
NEGATIVE
FLIGHT SPEED V

FIGURE 4.
COMPARISON OF n-V DIAGRAMS OBTAINED BY DIFFERENT METHODS

17. A further point may be mentioned here. If the *unfactored* loads correspond to frequently occurring manœuvres, and are associated with appropriately large factors, it is quite possible for the *factored* loads to be physically impossible. They may, for example, correspond to speeds above the terminal velocity of the aeroplane, obviously a state of affairs for which we need not cater. Thus to ensure that proof and ultimate loading are so far as possible physically practicable conditions the factors should be minimised and a rare frequency n-V boundary used. The present trend is to use proof factors of $1\frac{1}{8}$ and ultimate factors of 1.5—a compromise between the old ultimate factor of 2.0 and what is apparently the more logical ultimate factor of 1.33. There is, however, much to be said for modifying our habits slowly as the small excess factor of ignorance included in the proof value of $1\frac{1}{8}$ serves to cover many as yet unknown quantities, such as errors in assumed load distribution, effects of structural distortion, and so on.

Structural Variation.

18. One of the problems in the rationalisation of strength requirements is the unfortunate fact that structures designed to be identical are actually very variable. The variations in material strength, in the dimensions of the parts, and in workmanship, lead to a variation in the strength of apparently identical structures. The present inspection system aims to ensure that the materials used have strength properties not lower than certain minimum values, and that the dimensions lie within a certain range. Current design practice is to assume that the materials used in the construction of the aeroplane have minimum strength properties, and in the case of the sheet materials which make up the majority of the structure, that

the dimensions lie midway between the upper and lower specified limits. There are thus two main unknown quantities—in the materials themselves we do not know how much higher the average strength is than the minimum strength specified—and in the completed structure we do not know to what extent material variations results in variation of the strength of the structure.

TABLE I.

VARIATION OF MATERIAL PROPERTIES.

Failing Stress lying between (tons/sq. in.)	Number of Specim	
25 to 26	1	—— Specification minimum (26 tons/sq. in.)
26 to 27	3	
27 to 28	6	
28 to 29	12	
29 to 30	25	—— Mean failing stress ($30\frac{1}{4}$ tons/sq. in.)
30 to 31	28	
31 to 32	13	
32 to 33	7	
33 to 34	4	
34 to 35	1	

19. Table 1 shows typical (but hypothetical) results of 100 strength tests on a material. The average failing stress is $30\frac{1}{4}$ tons per sq. in., but in order to ensure that the rejection rate is not too high, the specified minimum strength (which the designer uses for strength calculations) is set at the low value of 26 tons per sq. in. To make the most effective use of materials it is clear that the designer should have more information on the average stresses and the scatter from the average.

20. In the present types of complex structure in which strength is dependent on several separate structural units (such as several sheets of material), it is likely that the variation of strength between the several sheets will to some extent cancel out. Thus the width of the scatter band for the complete structure is likely to be less than that of the individual structural units. This is a matter which can best be investigated by extensive testing to obtain statistical data.

21. The final linking together of the loading data and the strength of the completed aeroplane must evidently take into account both the frequency of occurrence of external loading and the variation of strength of structures. Dr. A. G. Pugsley, in R. and M., 1906, "A Philosophy of Aeroplane Strength Factors," has already shown the way "to weld these various aspects of the design of aeroplane structures into a logical and consistent whole." I will not attempt to reproduce the method here, but the interested reader would do well to refer to the original report which presents the solution to a somewhat involved problem with delightful clarity.

PRESENT TREND.

22. To gather together the threads of the preceding discussion, there are three clear trends to be observed. Each of these is at present becoming a practical possibility.

(*a*) The first is the use of the *V-G* data to establish the general shape of the design *n-V* diagram.

(*b*) The second, closely allied to and developing from the first, is the selection of an *n-V* boundary of given frequency of occurrence associated with factors (ultimate) of 1.5.

(*c*) The third is the use in design of stresses more closely related to the actual properties of the material.

Future Trend.

23. We may reasonably expect, as a development of the present trend, that more and more statistical data relating to external loading and to material variation will be collected. Statistical data on the variation of strength of the completed structure needs to be collected extensively, and the relationship of this variation with that of the component materials requires study. It is also necessary to devote more attention to the significance of proof and ulimate failure in causing accidents. When such information becomes available we should be able to abandon specifying strength in terms of two rather arbitrary conditions of failure and instead to employ the idea of *accident freedom*.

24. Whether or not our " factors of habit " will eventually disappear, I cannot say, but I suggest that our aim should be to amass and publish a body of statistical data relating to external loading and structural variation so that our handbooks of strength requirements may be reduced to a single statement to the effect that, " The designer shall produce evidence that the probable rate of accidents likely to cause injury to personnel arising from structural failure is not more than once in ' x ' thousands of hours of flying." If this aim is constantly borne in mind, even if not achieved, we shall at least ensure that such habits as are forced on us will be logical ones.

Acknowledgment.

25. Much of the original work which forms the background to this article was conducted by Dr. Pugsley and his staff at the Royal Aircraft Establishment. I should like to thank my colleagues there for many helpful discussions. I am indebted to the Air Registration Board for permission to publish this article, but I accept responsibility for opinions expressed.

THE DESIGN AND OPERATION OF SUPERCHARGERS

By A. J. Penn, A.M.I.Mech.E.

A Paper prepared and read before the Royal Aeronautical Society, Graduates' and Students' Section.

Introduction.

Initially, supercharging of aero-engines was introduced with a view to restoring the pressure in the induction manifold at altitude to that corresponding to sea level. During recent years this has been changed, and supercharging is now employed not just to maintain sea level pressure in the induction manifold, but to boost engines at altitude, in order to develop high B.M.E.P.s and thereby obtain high power outputs at high power to weight ratios.

The type of supercharger which has been universally adopted for the modern aero-engine is that of the centrifugal type. This type is essentially a high-speed machine, and therefore for a specific capacity has a low weight ratio and is compact and easy for installation.

Other types of superchargers, such as the Roots and Vane types, are entirely unsuitable, as apart from the question of reliability, these types would be relatively heavy and of such dimensions as to make them difficult to embody in aero-engine design.

The Centrifugal Type of Supercharger.

Briefly the centrifugal supercharger comprises a single- or double-sided rotating impeller enclosed between two half casings containing fixed diffuser vanes. The impeller is usually gear-driven through increasing gears from the engine, and according to the altitude performance requirements may have a single-speed, two-speed or variable-speed drive.

The alternate method of drive which has recently been perfected after years of research and development is the exhaust-turbine, and this is attractive for attainment of maximum engine power at great heights by utilisation of the energy left in the exhaust gas.

Fig. 1 shows an arrangement of a single-stage centrifugal supercharger. Air inhaled through the intake, "A," enters the impeller, "B," near its axis, and while flowing out through the impeller is given a high tangential velocity. The air then enters the diffuser, "C," in a spiral path between the fixed vanes, "D," during which the kinetic energy imparted to the air is converted into pressure with a rapid reduction of its peripheral velocity. The air leaving the diffuser passes through the delivery volute, "E," to the engine induction system.

Design of the Centrifugal Supercharger.

Inlet Design.

The most suitable design for the inlet to the supercharger is definitely debatable, but in general it is agreed that the air-flow at the inlet should be axial, whatever design be employed, and evenly distributed on the impeller. Best results are generally obtained with a straight axial intake, but the difference, however, is not great if an intake manifold properly shaped and of ample dimensions be employed.

Impeller Design.

Various designs of impellers are employed in superchargers of different types of aero-engines manufactured in this and other countries; these types may be classified as follows: double-shrouded; single-shrouded; double-entry; single-entry. These may have integrally bent blades at entry or separate rotating steel guide vanes which may be of the machined or bent type. The single-shrouded, single-entry type impeller with straight radial blades, as shown on Fig. 1, is more generally used for simplicity of manufacture.

With this type of impeller it is essential that the clearance on the bladed side between the edges of the blades and the casing be a minimum, in order to reduce the losses due to leakage from the front side of the blades where the high pressure region exists, to the low pressure region at the back of the blades. It is for this reason that the fully-shrouded impeller has a slightly improved maximum efficiency.

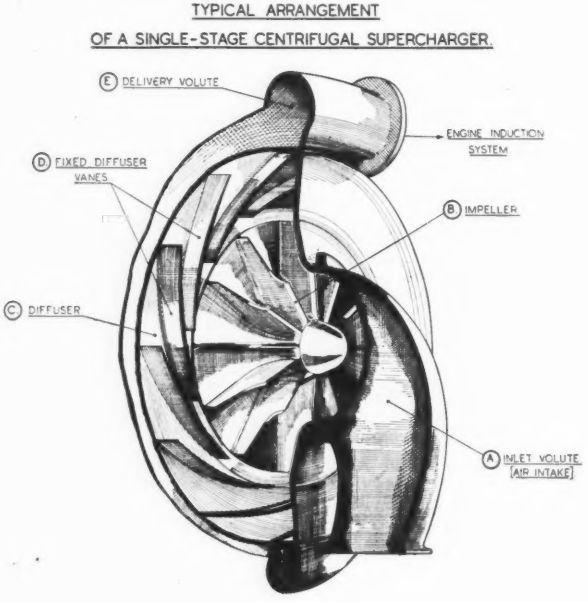


FIG. 1.

It is usual to give some degree of curvature to the blades at entry, in order that the air-flow may enter the impeller practically free from shock. When commencing to design an impeller, it is first necessary to calculate the tip speed for the compression ratio required. The outside diameter, D_2, of the impeller is then decided, in relation to the permissible overall dimensions of the projected supercharger and the maximum safe rotational speed for the degree of required reliability of the supercharger drive.

The number of blades selected for the impeller is a compromise; a large number reduces the relative eddy velocity and separation between the blades, but results in restriction at the entry of the impeller with resultant high velocity and increased friction. The balance for a specific design can be decided only as a result of experiments. In practice, the number of blades varies between 12 and 20.

The entry diameter, D_1, of the impeller is decided in relation to the weight of air to be inhaled to give the required engine performance. This is usually between .45 D_2 and .7 D_2, and is to a certain degree affected by the boss diameter, d, for the impeller spindle.

Fig. 2 shows the relationship between the entry diameter, D_1, and the mach factor, "M," i.e., the ratio of the absolute velocity to the acoustic velocity for the prevailing temperature conditions. The curve gives the optimum diameter, D_1, for the minimum mach factor, "M," and shows that it is preferable for the value of D_1 to be higher than the optimum rather than lower, as the curve rises rapidly for the smaller values of D_1.

Fig. 3 shows the velocity diagrams for the entry guide vanes, assuming a uniform axial flow at the entry, which in practice is usually not quite achieved due to a slight induced swirl.

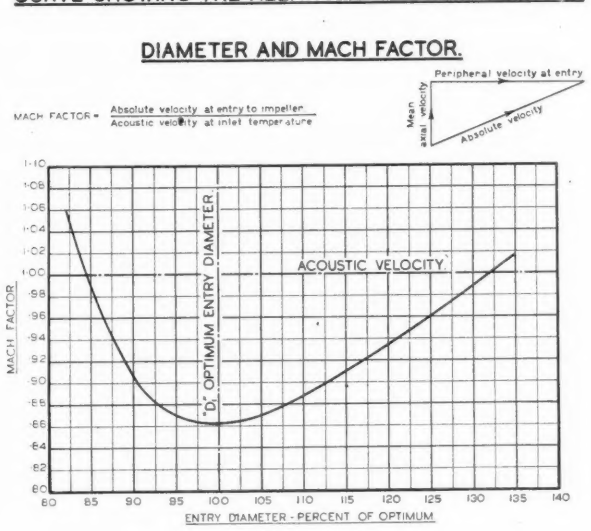


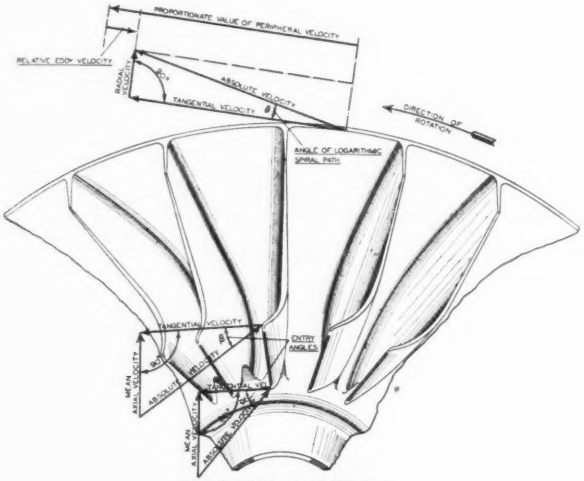
FIG. 2.

From the peripheral velocity at entry and the mean axial velocity of the air, it is possible to ascertain the absolute velocity and the entry angle for the entry outer diameter, D_1. From a similar process it is possible to calculate the entry angle at the impeller boss, that is, at the entry inner diameter, d. The angle to which the entry blades should be set at the outer diameter, D_1, is generally 20 to 40 degrees, and that at the inner diameter, d, in the vicinity of the boss, 30 to 60 degrees. These angles are usually calculated to ensure maximum efficiency for maximum flight performance.

The impeller disc profile is designed to give a safe stress in the disc and the blade contour so that the sectional areas through the channels follow a smooth curve from entry to the periphery.

The area at the periphery of the impeller should be as small as possible, provided that it does not result in too large a log spiral angle. Log spiral angles usually employed range between 10 and 20 degrees, depending upon the altitude at which maximum performance of the supercharger is required.

Fig. 3 shows also the velocity diagram and log spiral angle at the periphery of the impeller, allowing for the effect of the relative eddy velocity but not for separation.



VELOCITY DIAGRAMS
AT ENTRY & PERIPHERY OF IMPELLER.

FIG. 3.

TYPICAL STRESS CURVES FOR AN IMPELLER.

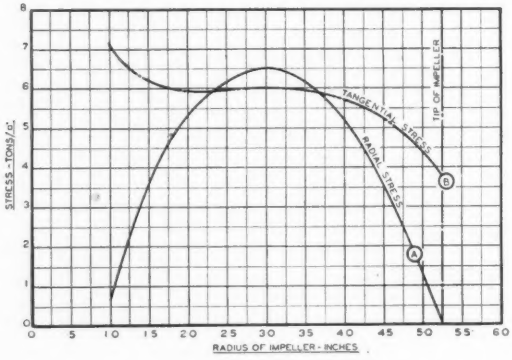


FIG. 4.

The tangential component of the air leaving the impeller for the radial blade type is less than the peripheral velocity, due to relative eddy. From the tangential velocity and the mean radial velocity it is possible to determine the absolute velocity and the log spiral angle of the air leaving the impeller.

The stressing of the impeller is involved and certain assumptions have to be made. On these assumptions the maximum stress in an impeller is usually at a point on the disc of approximately .6 D_2, and is in the neighbourhood of 6½ tons per square inch for an impeller manufactured in duralumin. Impellers tested to these criteria have proved to be satisfactory.

Fig. 4 shows the typical stress curves for an impeller. Curve A shows the radial stress in the disc and Curve B the tangential stress. Regarding the manufacture of impellers, until recently these were machined from a solid duralumin "cake," but they are now machined from die stampings.

Diffuser Design.

The function of a diffuser with fixed vanes surrounding the impeller at the periphery is to transform the kinetic energy imparted by the impeller to the air into pressure energy as quickly as possible and in the smallest space for compactness.

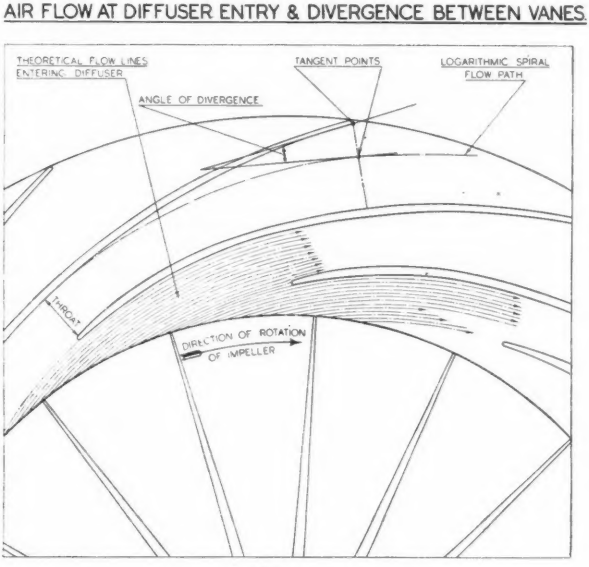

AIR FLOW AT DIFFUSER ENTRY & DIVERGENCE BETWEEN VANES.
THEORETICAL FLOW LINES ENTERING DIFFUSER
TANGENT POINTS
LOGARITHMIC SPIRAL FLOW PATH
ANGLE OF DIVERGENCE
THROAT
DIRECTION OF ROTATION OF IMPELLER

FIG. 5.

Fig. 5 shows the air-flow leaving the impeller and entering the diffuser. The energy in the air leaving the periphery of the impeller is partly kinetic and partly pressure.

If the air leaving the periphery of the impeller were allowed, it would form a free vortex co-axial with the impeller, and would flow in a spiral path to the delivery volute exit at the periphery of the casing. The velocity would be reduced and the pressure increased by the laws of vortex motion. To transform efficiently the kinetic energy of a high performance supercharger into pressure by this method would mean reducing the absolute velocity of the air leaving the impeller from 1,000 to 1,200 ft./second to approximately 200 ft./second. This would necessitate a casing of very large dimensions surrounding the impeller, and would be prohibitive in the case of aero-engine design, where compactness and weight are important considerations. It is for this reason that it is general practice in super-

charger design for aero-engines to employ a fixed vane diffuser to hasten the transformation of the kinetic energy into pressure.

When a vaned diffuser is employed, it is essential that a free vortex space with converging boundary walls be provided between the impeller and diffuser to steady the air-flow into a uniform condition before entering the passages between the diffuser vanes.

The design of a diffuser can be correct for one condition only, as a change of rate of air-flow at the same impeller tip speed would alter the log spiral angle of the air leaving the impeller, and this would necessitate adjustment of the diffuser angle. It is therefore usual to design a diffuser for the maximum rate of air-flow at the maximum power altitude in flight.

Before commencing to design the diffuser it is necessary to proportion (1) the gap between the impeller and diffuser, (2) the radial depth of the diffuser, and (3) the size of the delivery volute, in relation to the overall dimensions of the supercharger permissible by the layout of the projected engine.

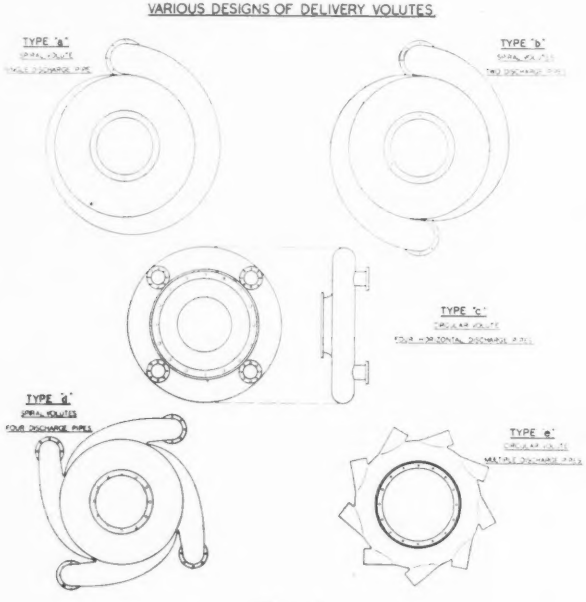


FIG. 6.

The radial distance between the impeller and diffuser is usually about 0.05 D_2, therefore D_3, at the entry of the diffuser vanes, is approximately 1.10 D_2, the outer diameter, D_4, of the diffuser vanes usually varies between 1.40 D_2 and 1.60 D_2. The ranges of these ratios in terms of impeller diameter, D_2, are established as a result of previous experiments. The selection of the number of blades for the diffuser is influenced by the delivery volute design which in turn is influenced by the engine induction system, which depends upon the type of engine and the cylinder arrangements. If the induction system comprises two manifolds, the number of vanes should be even; and if it comprises four manifolds, the number of vanes should be a multiple of four. If, however, a single manifold be employed or there be separate pipes from each cylinder to a delivery collector ring, any number of vanes can be used.

In practice, the number of vanes varies between eight and twenty, depending upon their thickness and shape and the log spiral angle.

The cross-sectional shape between the vanes is usually rectangular in aero-engine supercharger design, but it is generally considered that a square cross-sectional passage throughout gives an improved efficiency.

The contour of the vanes is designed to give the required expansion characteristic, previously established as a result of considerable research. The rate of expansion through the diffuser passages is one of the most important factors of the design. The internal contour of the vanes is designed to follow the log spiral angle curve up to the throat formed by the two consecutive vanes, in order to avoid shock to the air at entry. From this point, the vane contours are designed with a certain angle of divergence from the log spiral curve to forcefully divert the air from its free log spiral path to hasten the transformation of the kinetic energy into pressure.

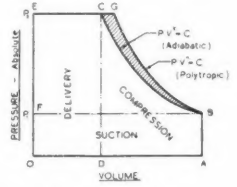
The design of the vanes at the exit should be such that the velocity of the air leaving the diffuser is reduced to within 200 to 300 ft./second.

PRESSURE - VOLUME DIAGRAM OF WORK DONE IN THE CENTRIFUGAL SUPERCHARGER.

SYMBOLS

P_1 = INITIAL PRESSURE ..... LB/SQ.FT. Absolute
V_1 = " " VOLUME ..... CU.FT.
T_1 = " " TEMPERATURE ..... Absolute
P_2 = FINAL PRESSURE ..... LB/SQ.FT. Absolute
V_2 = " " VOLUME ..... CU.FT.
T_2 = " " TEMPERATURE ..... Absolute
R = GAS CONSTANT
K_p = SPECIFIC HEAT OF GAS AT CONSTANT PRESSURE
γ = RATIO OF SPECIFIC HEATS
W = WEIGHT OF AIR ..... LB/MINUTE
r = COMPRESSION RATIO
η_a = ADIABATIC EFFICIENCY
η_m = MECHANICAL EFFICIENCY

H.P. ABSORBED BY SUPERCHARGER $= \frac{W K_p T_1}{33000 \eta_m \eta_a}\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] = \frac{W T_1}{98.5 \eta_m \eta_a}\left(r^{\frac{\gamma-1}{\gamma}} - 1\right)$



SUCTION
WORK DONE = W_s = AREA ABFO = $P_1 V_1$ Ft. lb.

COMPRESSION
WORK DONE = W_c = AREA ABCD = $\frac{P_2 V_2 - P_1 V_1}{\gamma - 1} = \frac{W R T_1}{\gamma - 1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$ Ft. lb.

DELIVERY
WORK DONE = W_d = AREA DCEO = $P_2 V_2$ Ft. lb.

TOTAL FOR CYCLE
WORK DONE = W_t = AREAS DCEO + ABCD − ABFO = BCEF = $\frac{\gamma}{\gamma - 1}(P_2 V_2 - P_1 V_1) = W K_p T_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$ Ft. lb.

FIG. 7.

Delivery Volute Design.

As stated previously, the design of delivery volute is influenced by the form of the engine induction system, which depends upon the type of engine and the arrangement of the cylinders.

Fig. 6 shows various designs of delivery volutes employed for different types of engines; in all cases a diffuser with fixed vanes can be used between the impeller and volute. Delivery volutes (a) to (d) are suitable for "in-line" engines, and delivery volute (e) for radial engines where each exit pipe is connected direct to each engine cylinder.

The cross-sections of these delivery volutes may be either rectangular or circular. The circular cross-section, however, is considered to be the most efficient. Careful consideration is necessary in the design of the delivery volute, as generally the conversion of energy at the exit of the vaned diffuser is not complete, and a further recovery of pressure is possible with careful design, as the air passes through the volute. Delivery volute losses, however, although important, are not so serious as intake losses.

THE THEORY OF THE CENTRIFUGAL SUPERCHARGER.

The function of a centrifugal supercharger is to deliver air to the engine at an increased pressure by centrifugal action. The process which takes place in the supercharger is that air in the impeller passages is forced outwards to the periphery due to rotation of the impeller, and this displacement creates a suction at the entry which induces more air to flow into the impeller from the air intake. As the air passes through the impeller to the diffuser, work is done on the air by increasing its moment of momentum. The amount of work done on the air by the impeller depends on its diameter and speed of rotation.

The air as it enters the diffuser possesses kinetic energy, and this is converted into pressure as the air passes through to the delivery volute. The greater the kinetic energy in the air, the greater the losses because the conversion is always accompanied by considerable shock losses. No work is done on the air by the diffuser.

Fig. 7 shows a P-v diagram of the work done in the centrifugal supercharger.

Symbols.

P_1 = Initial pressure..... lb./ft.^{2} Absolute.
v_1 = Initial volume..... cu. ft.
T_1 = Initial temperature..... Absolute.
P_2 = Final pressure.....lb./ft.^{2} Absolute.
v_2 = Final volume..... cu. ft.
T_2 = Final temperature.....Absolute.
R = Gas constant.
K_p = Specific heat of gas at constant pressure.
γ = Ratio of specific heats.
W = Weight of air..... .....lb./minute.
r = Compression ratio.
η_a = Adiabatic efficiency.
η_m = Mechanical efficiency.

If a volume of air, v_1, at a pressure, P_1, enters the impeller and is compressed to a pressure, P_2, the change of pressure with volume will be represented by Curve B.C. In an ideal uncooled supercharger where there is no transference of heat to or from the air, the compression will be adiabatic, and the expression for the Curve B.C is given by

$$Pv^{\gamma} = C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The adiabatic compression of the air from pressure, P_1, to pressure, P_2, is accompanied by a temperature rise which is given by equations

$$T_2 - T_1 = T_1\left[\left(\frac{P_2}{P_1}\right)^{(\gamma-1)\div\gamma} - 1\right] \quad . \quad . \quad . \quad . \quad . \quad (2)$$

or

$$= T_1\left[\left(\frac{v_1}{v_2}\right)^{(\gamma-1)} - 1\right] \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The work done during the adiabatic compression of the air from B to C is represented by the area A.B.C.D, and given by equations

$$W_c = \frac{(P_2v_2 - P_1v_1)}{(\gamma - 1)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

or

$$W_c = \left\{ \frac{RWT_1}{(\gamma - 1)} \right\} \left[\left(\frac{P_2}{P_1} \right)^{(\gamma-1)/\gamma} - 1 \right] . \quad . \quad . \quad . \quad (5)$$

The total work done by the supercharger in delivering air at increased pressure to the engine results from suction, compression and delivery.

The work done during the suction of air into the supercharger at pressure, P_1, is represented by the area A.B.F.O, and is done by the atmosphere in forcing the air into the supercharger, and is given by

$$W_s = P_1 v_1 \text{ ft. lb.} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The work done after compression in delivering the air at pressure, P_2, and volume, v_2, through the delivery volute to the engine is represented by the area D.C.E.O, and equals

$$W_2 = P_2 v_2 \text{ ft. lb.} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The total work done in inhaling air and delivering it at increased pressure to the engine is represented by the areas D.C.E.O + A.B.C.D − A.B.F.O = area B.C.E.F, and can be expressed in terms of pressures and volumes as follows:—

$$W_t = P_2 v_2 + \frac{(P_2 v_2 - P_1 v_1)}{(\gamma - 1)} - P_1 v_1$$

$$= \left\{ \frac{\gamma}{(\gamma - 1)} \right\} (P_2 v_2 - P_1 v_1) \quad . \quad . \quad . \quad . \quad (8)$$

A convenient form of expressing the equation is

$$W_t = WK_p T_1 \left[\left(\frac{P_2}{P_1} \right)^{(\gamma-1)/\gamma} - 1 \right] \quad . \quad . \quad . \quad . \quad (9)$$

The equations given above are for an ideal uncooled centrifugal supercharger and give the theoretical work done with adiabatic and frictionless compression, whereas in the case of an actual uncooled supercharger the compression is not truly adiabatic and the work done is always greater due to friction, shock and eddying which results in a conversion into heat.

The additional work done during compression in the case of an actual supercharger is represented by the shaded area B.G.C and the total work done by area B.G.E.F.

To determine the actual work done it is necessary to introduce an efficiency in equations (8) and (9), and this is known as the "adiabatic efficiency," and denoted by symbol η_a. This efficiency is expressed as a ratio

$$\frac{\text{Work done with adiabatic and frictionless compression}}{\text{Actual work done during compression.}}$$

The actual horse-power absorbed by a centrifugal supercharger in compressing W lb. of air per minute from a pressure, P_1, to a pressure, P_2, and delivering it to an engine, can be computed from the equation given below, provided that the mechanical efficiency of the drive, η_m, and the adiabatic efficiency, η_a, are known.

$$\text{H.P.} = \frac{WK_p T_1 \left[\left(\frac{P_2}{P_1} \right)^{(\gamma-1)/\gamma} - 1 \right]}{(33000\ \eta_a \eta_m)} \quad . \quad . \quad . \quad . \quad (10)$$

K_p = Specific heat of air at constant pressure = 335 ft. lb./lb. °C.

and

P_2/P_1 = Compression ratio of supercharger = r.

Therefore, a simplified form is

$$\text{H.P.} = \frac{WT_1 (r^{\gamma-1/\gamma} - 1)}{(98.5\ \eta_a \eta_m)} \quad . \quad . \quad . \quad . \quad . \quad (11)$$

It can be seen from this equation that if the efficiencies of the supercharger remain constant, the horse-power absorbed by the supercharger is a function of the mass flow of air, the initial temperature and the compression ratio.

Fig. 8 shows the typical pressure distribution and velocity changes of the air as it flows through the various stages of a centrifugal supercharger fitted with an impeller with radial blades. The nature of the energy changes that take place as the air passes through the impeller can be seen by analysis of the equation. For simplicity, an incompressible fluid has been assumed.

$$E = (1/2g)\left[(V_2^2 - V_1^2) + (U_2^2 - U_1^2) + (V_{r1}^2 - V_{r2}^2)\right] \quad . \quad . \quad (1)$$

In which

E = Energy given to the fluid passing through the impeller.
V_1 = Axial velocity entering impeller.
V_2 = Absolute velocity leaving impeller.
U_1 = Peripheral velocity—inlet of impeller.
U_2 = Peripheral velocity—tip of impeller.
V_{r1} = Relative velocity of fluid—inlet of impeller.
V_{r2} = Relative velocity of fluid—tip of impeller.
η = Efficiency.
g = Acceleration due to gravitation.

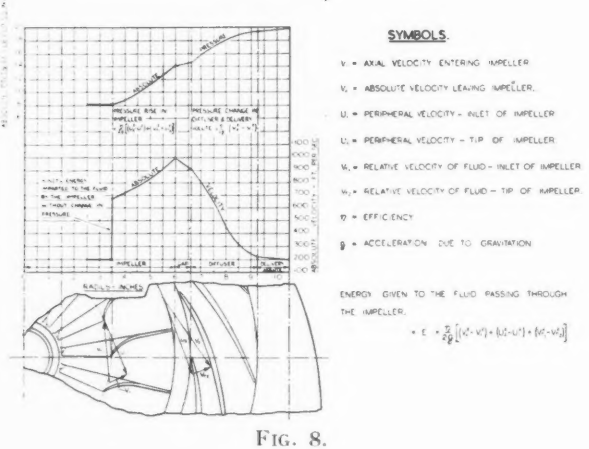

TYPICAL PRESSURE & VELOCITY CHANGES OF THE AIR
PASSING THROUGH A CENTRIFUGAL SUPERCHARGER
SYMBOLS.
V1 = AXIAL VELOCITY ENTERING IMPELLER.
V2 = ABSOLUTE VELOCITY LEAVING IMPELLER.
U1 = PERIPHERAL VELOCITY - INLET OF IMPELLER.
U2 = PERIPHERAL VELOCITY - TIP OF IMPELLER.
Vr1 = RELATIVE VELOCITY OF FLUID - INLET OF IMPELLER.
Vr2 = RELATIVE VELOCITY OF FLUID - TIP OF IMPELLER.
η = EFFICIENCY.
g = ACCELERATION DUE TO GRAVITATION.
ENERGY GIVEN TO THE FLUID PASSING THROUGH THE IMPELLER.
= E = 1/2g [(V2² - V1²) + (U2² - U1²) + (Vr1² - Vr2²)]
ABSOLUTE
RELATIVE
IMPELLER
DIFFUSER
DELIVERY VOLUTE

FIG. 8.

The first term in the equation, $(1/2g)(V_2^2 - V_1^2)$, represents the change in kinetic energy of the fluid as it passes through the impeller. Fluid entering the impeller at an axial velocity, V_1, and leaving with an absolute velocity, V_2, experiences a change of kinetic energy, which is received from the impeller. This change of kinetic energy is converted into a pressure change in the diffuser and delivery volute.

The second term in the equation, $(1/2g)(U_2^2 - U_1^2)$, represents the change of pressure due to centrifugal force in the impeller as a result of rotation. As the velocity of U_2 is greater than U_1, the fluid flows radially and a change of centrifugal force takes place, and this results in a pressure difference.

The final term, $(1/2g)(V_{r1}^2 - V_{r2}^2)$, represents the pressure rise due to the change in relative velocity of the fluid as it passes through the impeller.

The centrifugal and change of relative velocity effects combined give the pressure change across the impeller, which equals

$$(\eta/2g)\left[(V_2^2 - V_1^2) + (V_{r1}^2 - V_{r2}^2)\right] \quad . \quad . \quad . \quad (2)$$

An efficiency, η, has been introduced as the change involves losses, such as friction, shock and eddying.

Term $(\eta/2g)(V_2^2 - V_1^2)$ gives the pressure change in the diffuser and delivery volute, and added to this equation (2) gives

$$(\eta/2g)[(V_2^2 - V_1^2) + (U_2^2 - U_1^2) + (V_{r_1}^2 - V_{r_2}^2)]$$

In other words, the impeller energy, multiplied by an efficiency factor, results in the fluid energy as found by total pressures at the entrance and exit of the supercharger.

An incompressible fluid has been assumed to simplify this analysis, but a similar analysis can be given for a compressible gas such as air.

In the foregoing it has been possible to only briefly describe the theory owing to the limited time available.

Supercharger Performance Calibration.

The determination of the pressure-volume and efficiency characteristics of a centrifugal supercharger on the test-rig necessitates conducting a series of constant speed characteristic curves at different speeds covering the operating range of the supercharger when installed on the engine.

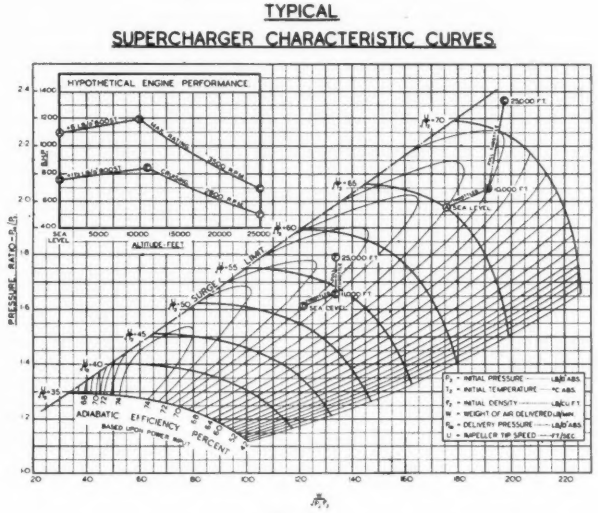


Fig. 9.

Fig. 9 shows a typical supercharger air-flow calibration, which comprises a series of constant speed characteristic curves covering a range of impeller speeds up to 26,000 R.P.M., with adiabatic efficiency curves superimposed upon the pressure ratio characteristics. Each constant speed characteristic curve was commenced at the maximum mass flow, which was reduced in increments by gradually closing the inlet valve until ultimately the minimum flow at surge point was reached. Surging is usually denoted by an abrupt decrease of delivery pressure, and is generally accompanied by audible air vibration.

Surging is an undesirable feature of the centrifugal supercharger and occurs at small rates of air-flow, and is generally accompanied by a sudden breakdown in the relation between the delivery pressure and mass flow.

The diffuser entry angle influences the surge point, the smaller angles being more beneficial in postponement of surging.

It will be seen from Fig. 9 that the optimum efficiencies are obtained at the smaller rates of air-flow in the vicinity of the surge point, and therefore, to obtain maximum engine performance, the supercharger should be of such capacity that when installed on the engine the operating points be in this region, but not too close to the surge point, otherwise instability will be experienced.

The diagram at the top left-hand corner of Fig. 9 shows the performance of a hypothetical engine with a maximum rating of +6 lb./sq. in. boost pressure at 3,500 engine R.P.M., and a cruising rating of +1½ lb./sq. in. boost pressure at 2,800 engine R.P.M. Line A.B represents the powers available under throttled conditions of +6 lb./sq. in. boost pressure up to the full throttle height of 10,000 ft., and line B.C represents the powers available at full throttle at falling boost pressures up to an altitude of 25,000 ft. Similarly, lines D.E and E.F represent the powers available for cruising under throttled and full throttle conditions up to an altitude of 25,000 ft. These lines are plotted on the supercharger characteristic curves and indicate the points at which the supercharger would operate if geared to an engine of this capacity and operating under these conditions.

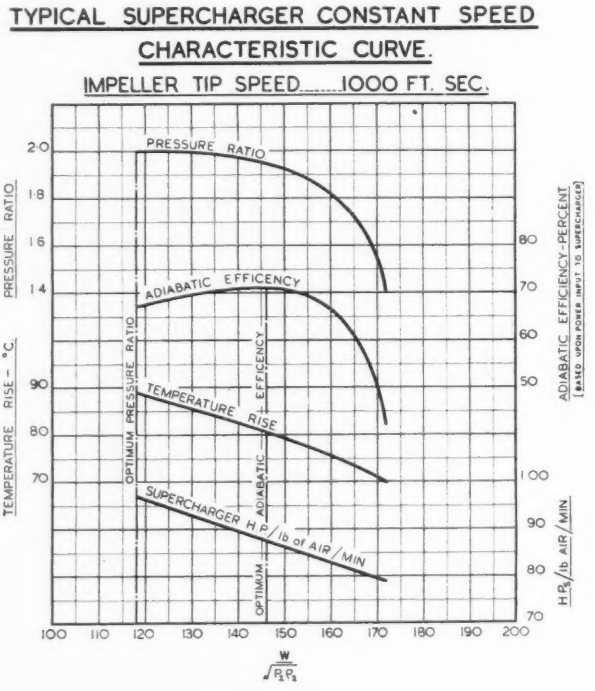


FIG. 10.

It is apparent from Fig. 9 that when the engine is operating under throttled conditions of constant boost pressure at altitudes above sea level, the supercharger will be operating at increased volumes of air, that is, at higher values of $W/\sqrt{P_2\rho_2}$, with only a slight variation in compression ratio. When the engine is operating at full throttle at altitudes above the full throttle height, the supercharger will be operating at approximately constant volume, that is, at a constant value of $W/\sqrt{P_2\rho_2}$, but with increased compression ratio.

It is important to remember when designing a supercharger that the engine controls the operating point of the supercharger and that the capacities of supercharger and engine must be carefully matched if maximum overall efficiency is to be obtained.

Fig. 10 shows a constant speed pressure ratio curve compared with an efficiency curve on the same mass flow basis at a tip speed of approximately 1,000 ft./second. It will be observed that the maximum adiabatic efficiency is not obtained at the same mass flow as that for the maximum compression ratio. This is explained by the fact that, as the mass flow of air through the impeller is increased from the "surge" point, the work done by the impeller on each unit mass of air gradually decreases, whereas the adiabatic efficiency increases to commence with, and then decreases rapidly. The effect of these two characteristics causes a slight decrease of compression ratio at first, and then a more rapid decrease, as the fall-off in adiabatic efficiency becomes the controlling characteristic.

The adiabatic efficiency depends upon how much of the energy given by the impeller to the air becomes dissipated into heat by shock eddies and friction. The decrease in efficiency at the larger mass flows is usually associated with increased heat produced by shock and friction during the diffuser stage.

Effect of Supercharging on Aero Engine Performance.

The effect of supercharging has allowed the modern aero-engine to be of relatively small displacement and medium compression ratio, and yet develop very high powers at sea level for "take-off" and also maintain high power outputs at high altitudes.

The maximum power output to which modern aero-engines can be boosted by supercharging is limited by detonation, which is dependent upon the octane value of the fuel available and induction temperature.

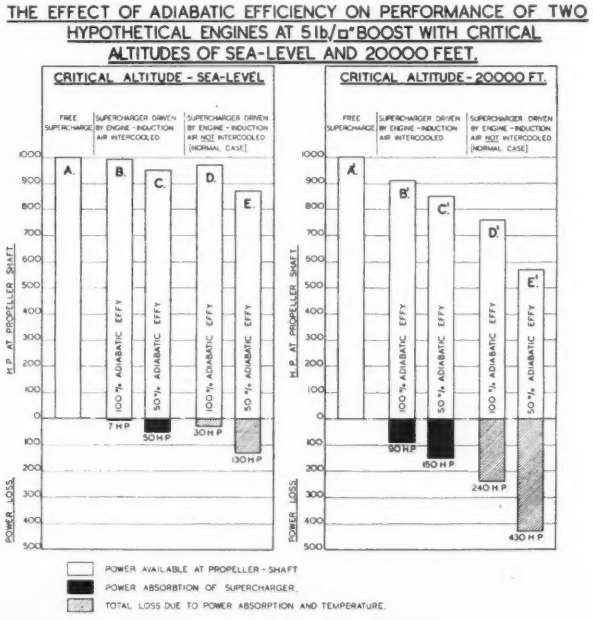


FIG. 11.

When two-stage superchargers are used for high boost at high altitudes, intercoolers are usually employed to reduce the induction manifold temperatures. Intercooling has a two-fold effect: (1) it increases the safety margin from detonation and (2) results in a denser charge to the cylinders, with consequent improvement in power output. The adiabatic efficiency of a supercharger has a considerable effect upon the horse-power absorbed by the supercharger and the final induction temperature, and consequently on the power available at the propeller shaft.

Fig. 11 illustrates the effect of adiabatic efficiency on the performance of two hypothetical aero-engines at 5 lb./sq. in. boost, one with a critical altitude of sea level, and the other with a critical altitude of 20,000 feet.

Assuming that the supercharger is driven independently from the engine and the induction air is intercooled to the initial air temperature, there would be no supercharger losses, and therefore 100 per cent. power available at the propeller shaft in both cases of critical altitude, as indicated by A and A^1, which represent an engine developing 1,000 B.H.P.

If the supercharger be driven from the engine and the induction air intercooled, there would be a loss of 7 B.H.P. at 100 per cent. adiabatic efficiency and 50 B.H.P. at 50 per cent. efficiency for sea level supercharger, as indicated by B and C.

In the case of the 20,000 ft. supercharger there would be 90 B.H.P. loss at 100 per cent. efficiency and 150 B.H.P. loss at 50 per cent. efficiency, as indicated by B^1 and C^1.

If the supercharger be driven from the engine and the induction air not intercooled (normal case), the total loss of power for the sea level supercharger would be 30 B.H.P. at 100 per cent. efficiency and 130 B.H.P. at 50 per cent. efficiency, as indicated by D and E. For the 20,000 ft. supercharger the loss of power would be 240 B.H.P. at 100 per cent. efficiency and 430 B.H.P. at 50 per cent. efficiency, as indicated by D^1 and E^1.

It is therefore very apparent that as the critical altitude of an engine is increased above that of sea level, the power available at the propeller shaft depends greatly on the adiabatic efficiency of the supercharger.

Engines fitted with single-speed superchargers maintaining constant boost pressure to high altitudes have comparatively low performances at low altitude and "take-off." The performance at low altitudes and "take-off" can be improved by the introduction of an additional gear ratio which will allow the supercharger to function at a reduced impeller tip speed and induction temperature when operating at "take-off" and low altitudes.

Fig. 12 shows the typical performance of a hypothetical engine fitted with a two-speed single-stage supercharger and boost control unit to control boost pressure. In this case there are two critical altitudes, one at 5,000 ft. and one at 20,000 ft.

The supercharger pressure ratio in low ratio gear at a critical altitude of 5,000 ft. is 1.61 to 1, and in high ratio gear at 20,000 ft. 2.92 to 1. At "take-off" the supercharger will be in low ratio gear with the impeller rotating at a tip speed of 800 ft./second, and the boost control will be in operation closing the throttle to maintain 5 lb. sq. in. boost pressure in the induction manifold, Curve B. As the altitude is increased the boost control unit will gradually open the throttle to maintain constant boost pressure at 5 lb./sq. in. until full throttle is reached in low ratio gear at 5,000 ft. At this point the boost control becomes inoperative, and as the altitude is further increased the boost pressure will progressively fall, a gear change being made into high ratio gear at 10,500 ft. Prior to the gear change the boost pressure will have fallen to +1.5 lb./sq. in.; immediately the gear change is made the impeller tip speed will be increased to 1,200 ft./second, and the boost control will therefore close the throttle to restrict the boost pressure to +5 lb./sq. in. As the altitude is increased in high ratio gear the boost control will gradually open the throttle to maintain the boost pressures until full throttle is

reached at 20,600 ft., the second critical altitude. Above this altitude the boost control will be inoperative, and as the engine is at full throttle the boost will fall progressively, nearly in proportion, but not quite as rapidly as the atmospheric pressure.

Curve A shows the power output available at the propeller shaft at various altitudes up to 30,000 ft., also that at the gear change altitude of 10,500 ft. the full throttle power in low ratio gear at +1.5 lb./sq. in. boost pressure is the same as the throttled power in high ratio gear at +5 lb./sq. in.

TYPICAL PERFORMANCE OF A HYPOTHETICAL ENGINE FITTED WITH A TWO-SPEED, SINGLE-STAGE SUPERCHARGER.

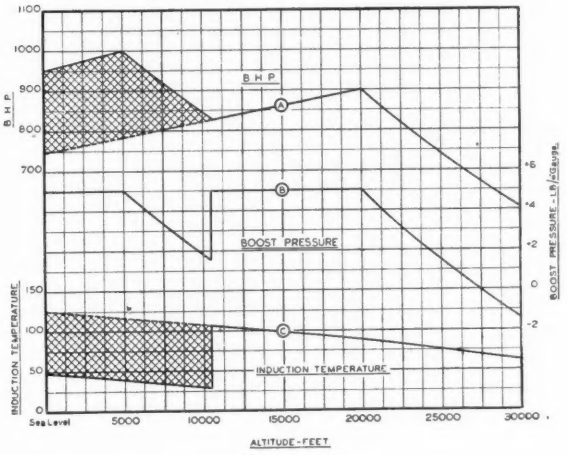


FIG. 12.

The induction temperatures at the various altitudes up to 30,000 ft. are indicated by Curve C.

The shaded areas on Fig. 12 show the gain in power output at the propeller shaft and decrease in induction temperatures at low altitudes and "take-off" resulting from the introduction of a low ratio gear.

Theoretically, the ideal arrangement for a gear-driven supercharger for supercharging aero-engines to high altitudes would appear to be one with an infinitely variable speed drive, which would allow the impeller speed to be adjusted to give full throttle performance at constant boost at all altitudes up to the critical. This arrangement, however, has certain disadvantages.

REVIEWS.

HANDBOOK FOR M.A.P. AND M.O.S. CONTRACTORS.

S. J. Noel-Brown, F.A.I.A., F.S.C.C., A.R.Ae.S., A.C.I.S., Engineering Industries Association, London. 1944. 7/6 net.

This is a Handbook of Reference for those unfortunate and misguided people who inadvertently become or are compelled to become Government contractors.

The author, in his preface, says: "The object of this handbook is an attempt to ease the lot of the contractor and to help him to understand the many conflicting contractural clauses as between one Ministry and another."

There are seven chapters, namely: Type of Contracts and Their Application; M.A.P. Conditions of Contracts; Ministry of Supply Conditions of Contracts; M.A.P. Sub-Contract Procedure; Analysis of M.A.P. and M.O.S. Conditions of Contract; Cost and Profit; and the 1944 Contract Conditions for M.A.P., M.O.S. and Admiralty Contracts.

Seven is a magic and mysterious number and this is a magic and mysterious book. Shakespeare wrote of the seven ages of man. The seventh age it may be recalled, "Is second childishness, and mere oblivion, sans teeth, sans eyes, sans taste, sans everything."

After the reviewer had digested some of the contractural clauses, so ably summarised by the author, the only conclusion he could come to was that Shakespeare had realised before most people, that to become a Government contractor is certainly likely to result in "mere oblivion, sans teeth, sans eyes, sans taste, sans everything," as far as the contractor is concerned.

This handbook should be placed in the hands of any firm who have not yet been caught up by the lure of Government contracts, so that he will not have the excuse he did not know. He will have the excuse in any case that he did not understand. The author has done an excellent job and one shudders to think how much man-power and man-hours have been required to interpret the clauses of man-power which would have been more usefully employed in many other directions.

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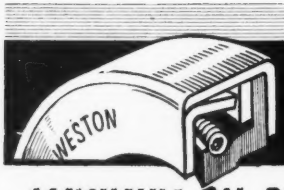

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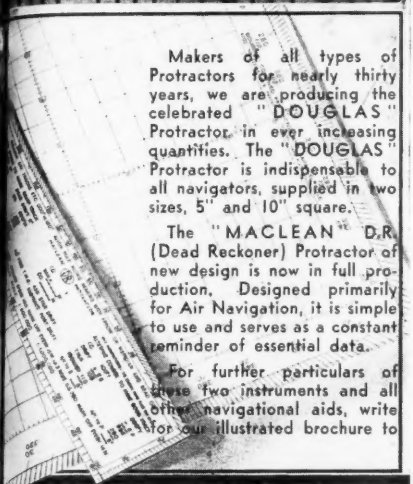

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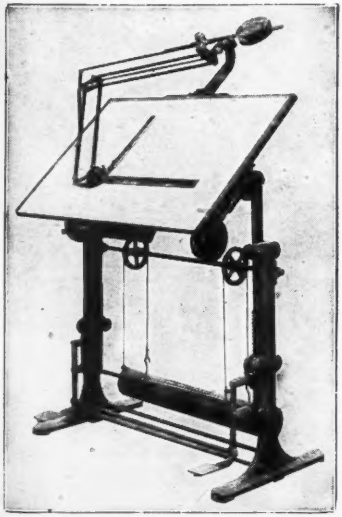

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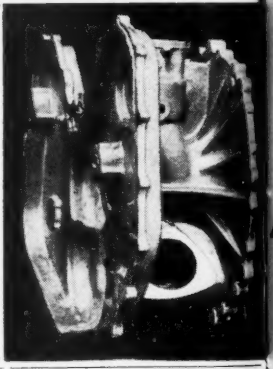

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This is a short resumè of the development of Newall bolts which are all branded with their distinctive marks.

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